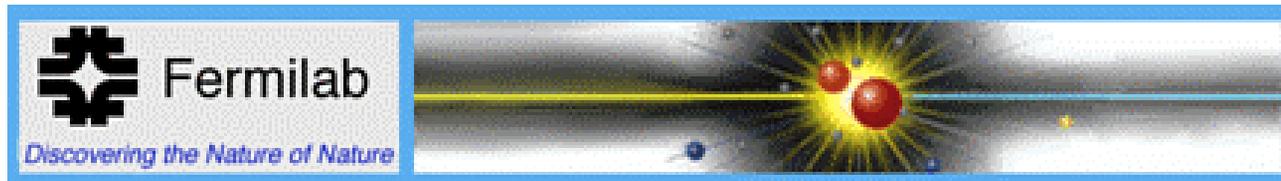


QCD Measurements at the Tevatron

Cecilia Gerber

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Les Rencontres de Physique de la Vallée d'Aoste

February 26 - March 4, 2000

Outline:

organize by final states:

- Jets
 - Cross Sections
 - BFKL
 - k_T algorithm
- W/Z
 - angular distributions
 - transverse momentum
- Photons
 - Cross Sections
 - Fixed target γ production

Data sets:

Collider Experiments (CDF&D0)

\overline{pp} at $\sqrt{s} = 1.8$ TeV

- Run 1A (92-93) $\int Ldt \sim 15 pb^{-1}$
- Run 1B (94-95) $\int Ldt \sim 90 pb^{-1}$
- Run 1C (95-96) $\int Ldt \sim 15 pb^{-1}$

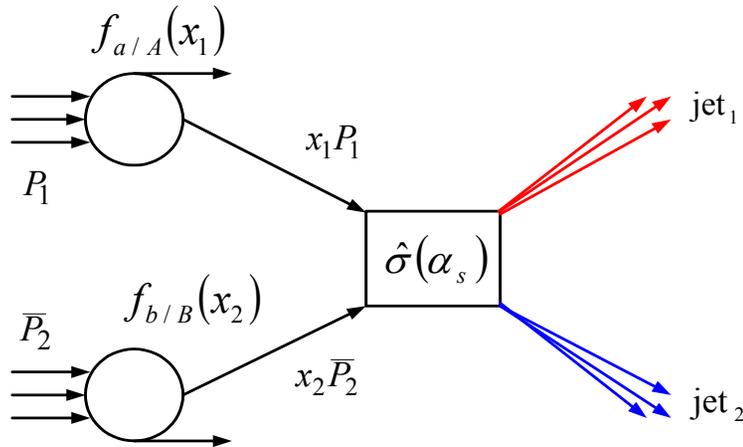
Fixed Target Experiments

(E706)

p, π , γ beams

- 1996-1997 running period

QCD and Jet Production



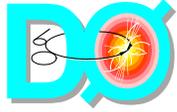
- What is the value of α_s ?
- How well do we know the proton structure ? PDFs: $f(x)$
- Is NLO (α_s^3) sufficient?
- Are quarks composite structures?

$$\sigma(p_1 \bar{p}_2 \rightarrow 2 \text{ jets}) = \sum_{abcd} \int dx_1 dx_2 f_{a/A}(x_1) f_{b/B}(x_2) \hat{\sigma}(ab \rightarrow cd)$$

- Jet Cross Section
(central region, η dependence, ratio of different cm energies)
 - Most simple test of NLO QCD
 - Probing BFKL
- k_T algorithm
 - Subject Multiplicity in quark and gluon jets.

Inclusive Jet Cross Section

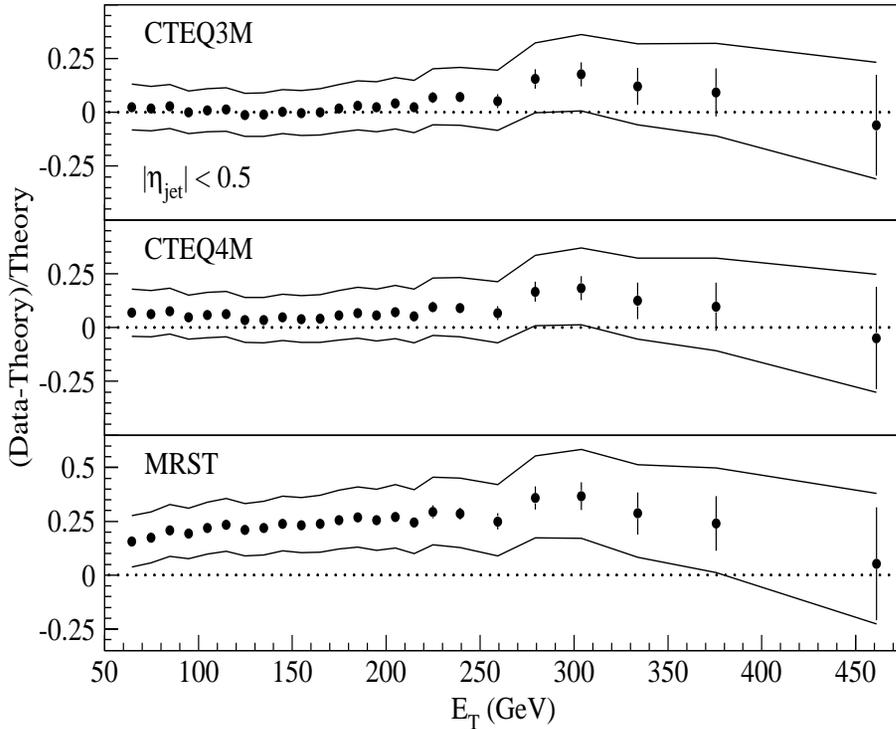
$$\frac{N_{jet}}{\varepsilon \Delta E_T \Delta \eta \int L dt} \quad \text{vs.} \quad E_T$$



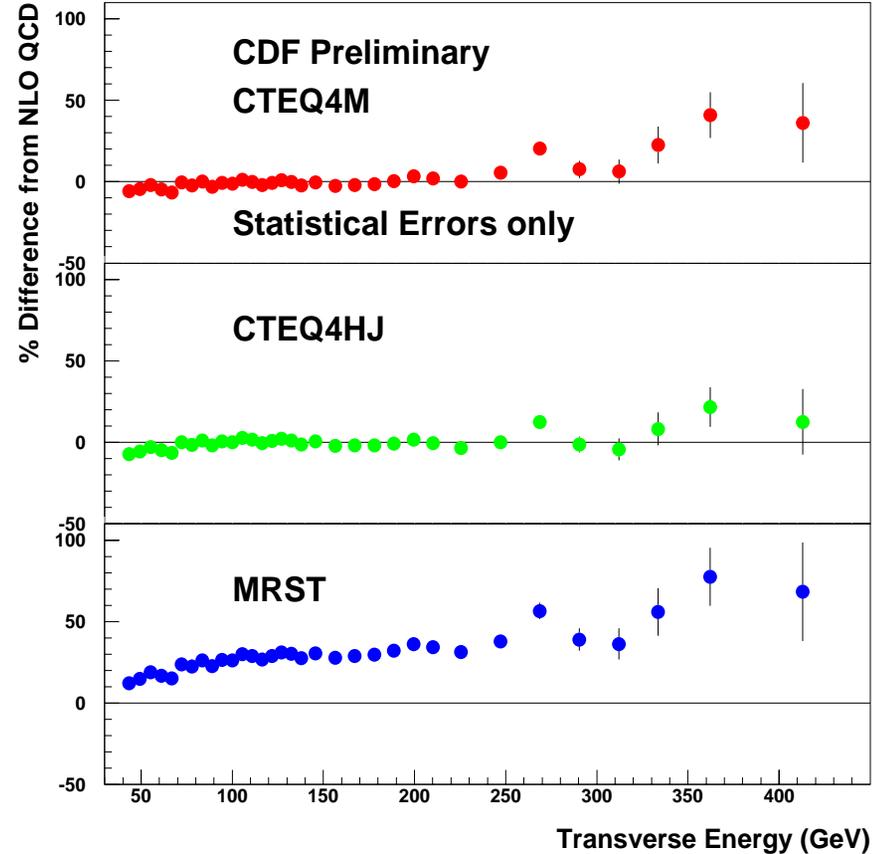
$|\eta| < 0.5$ PRL82, 2451 (1999)



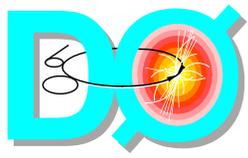
$0.1 < |\eta| < 0.7$ Preliminary



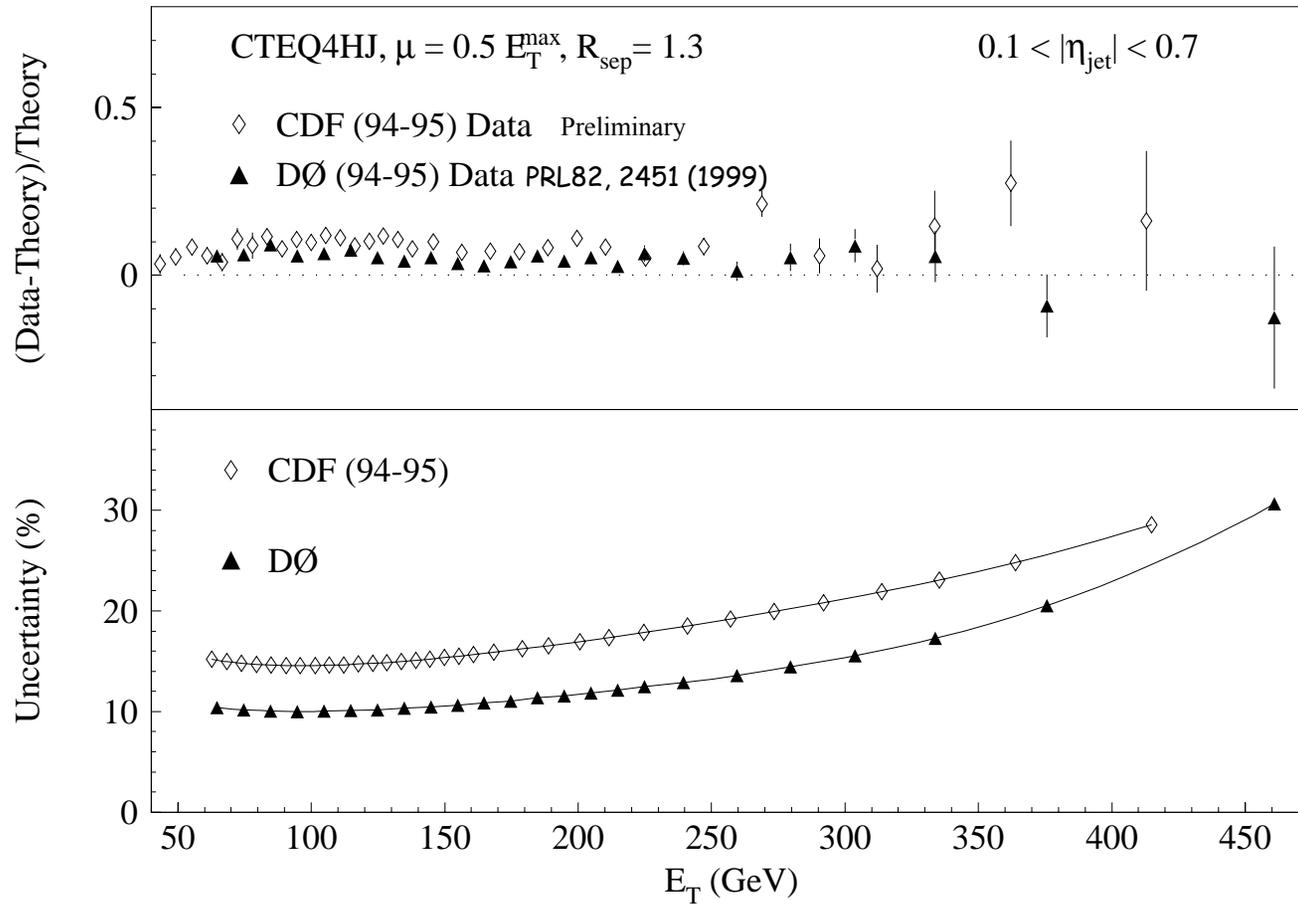
Data and theory agreement prob 47-90%



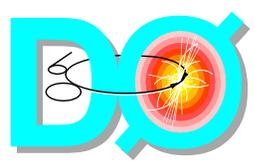
NLO QCD describes the data well



Inclusive Jet Cross Section at 1.8TeV



DO and CDF data in good agreement. NLO QCD describes the data well.



Rapidity Dependence of the Inclusive Jet Cross Section

$$\sqrt{s} = 1.8 \text{ TeV}, |\eta| < 3$$

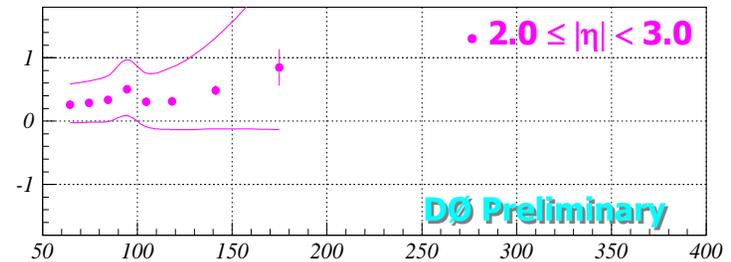
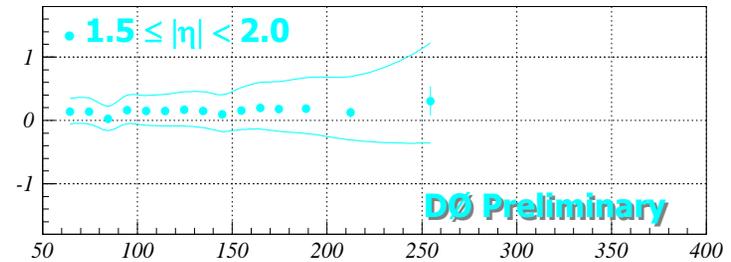
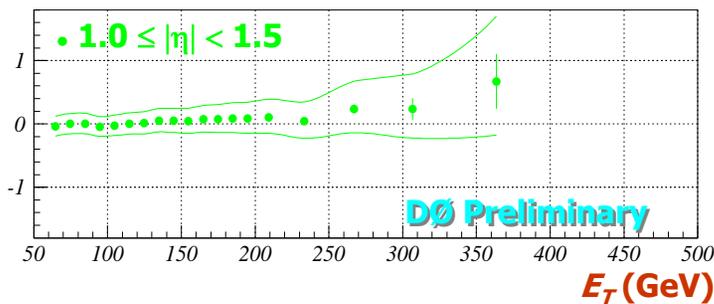
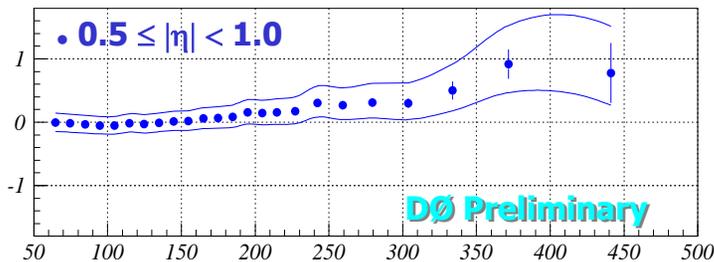
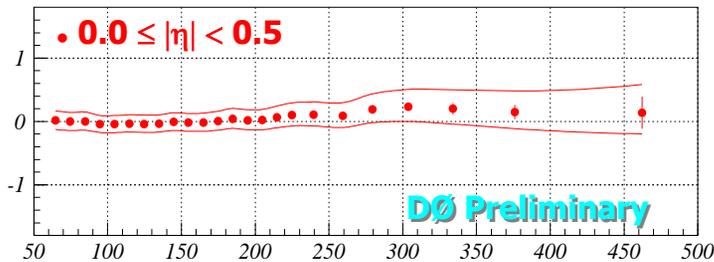
Comparisons to
JETRAD with:

PDF: CTEQ3M

$$\mu = E_T^{\text{max}} / 2$$

$$R_{\text{sep}} = 1.3$$

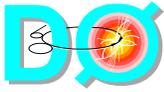
Data - Theory / Theory



E_T (GeV)

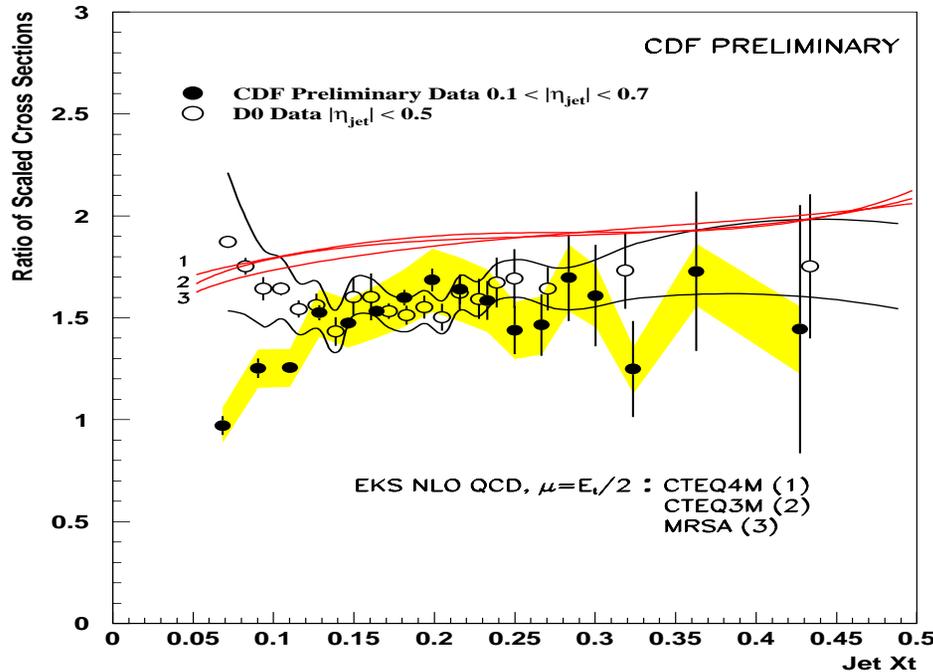
Data and NLO QCD
in good agreement for
 $0.0 \leq |\eta| < 3.0$

Ratio of Scale Invariant Cross Sections $\sigma_d(630)/\sigma_d(1800)$ vs x_T

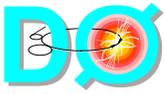


$$\sigma_d = (E_T^3/2\pi) (d^2\sigma/dE_T d\eta)$$

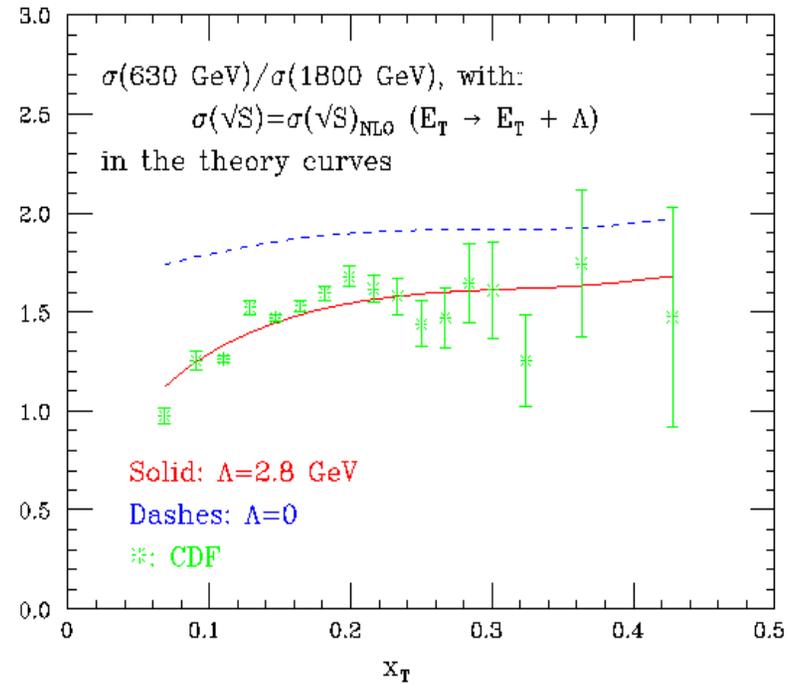
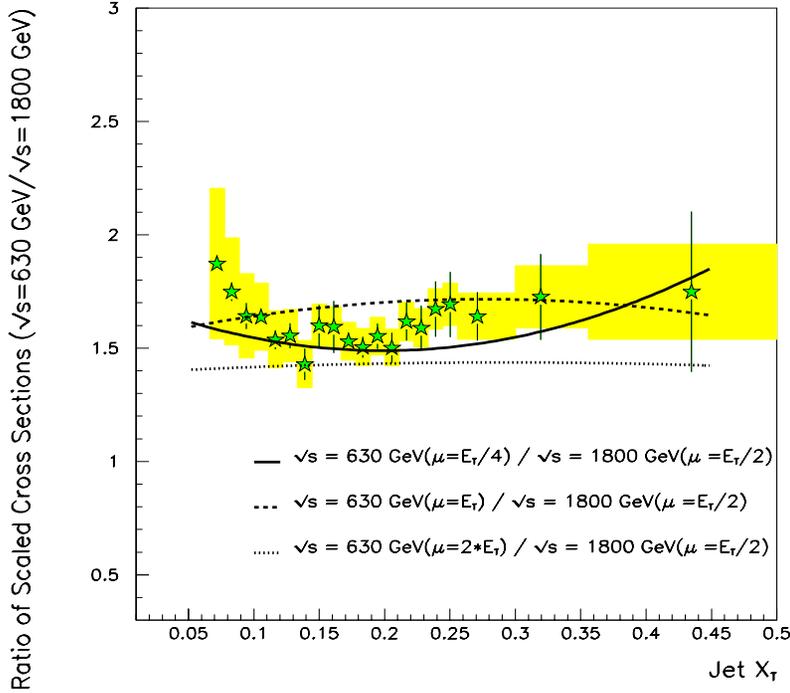
$$X_T = E_T / (\sqrt{s}/2)$$



Not obviously consistent with each other (especially at low x_T)
or with NLO QCD (at any x_T)



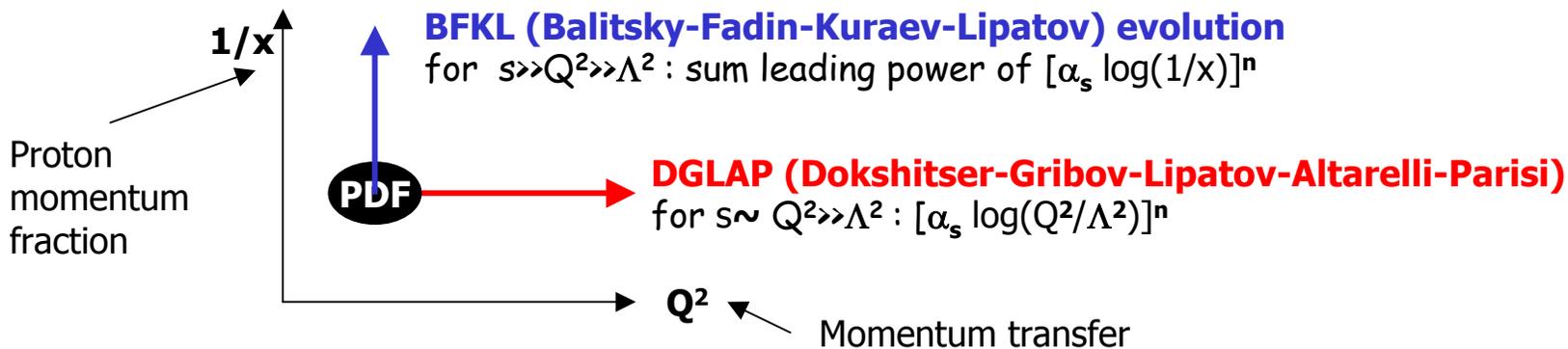
Ratio of Scale Invariant Cross Sections $\sigma_d(630)/\sigma_d(1800)$ vs x_T



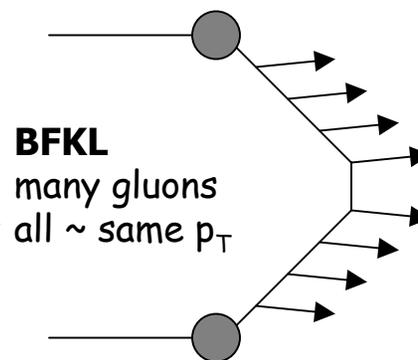
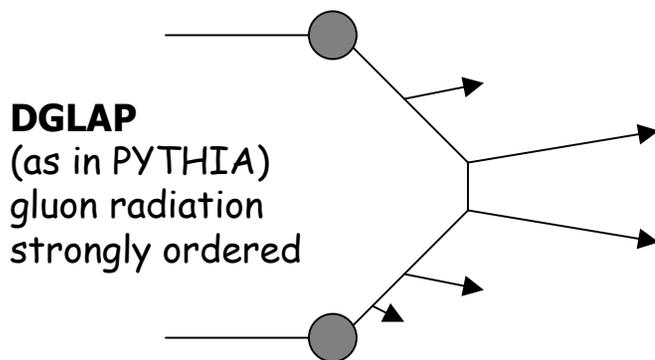
• Taking different renormalizations scales in theory for 630 vs 1800 GeV produces good quantitative agreement between D0 data and NLO QCD

• Mangano proposes an $O(3 \text{ GeV})$ non-perturbative shift in jet energy (losses out of cone, underlying event, intrinsic k_T) Could be different for D0 data.

BFKL

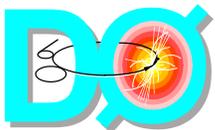


In hadron-hadron collisions:



One way to realize this situation is jets widely separated in rapidity: the total energy is then much greater than the jet p_T scale, and one can have many gluons of comparable p_T emitted between the jets

Note: BFKL provides a way to resum the contribution of these gluons; it doesn't predict how many there are, and there is no BFKL event generator yet



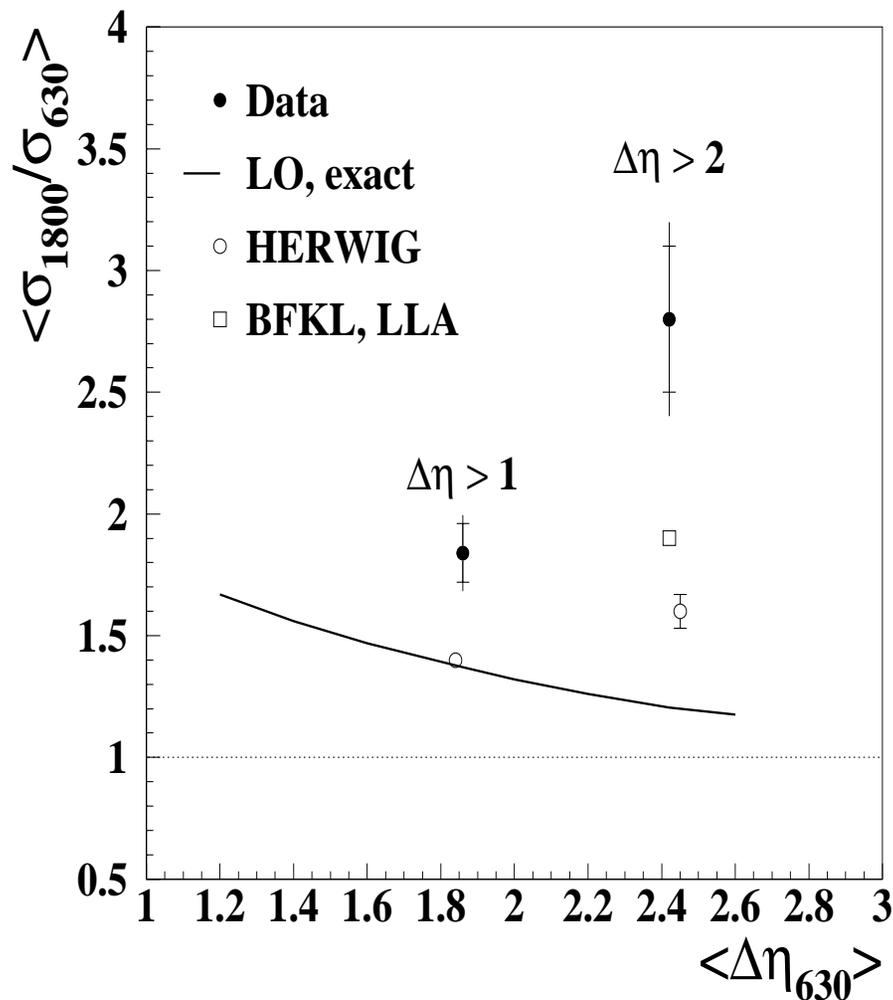
Dijet Cross Section at large $\Delta\eta$: probing BFKL

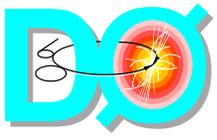
- Gold-plated analysis to search for BFKL dynamics
 - Measure Dijet Cross Section for $\Delta\eta > 2$ in (x_1, x_2, Q^2) bins at two center of mass energies: 1800 & 630 GeV.
 - Take cross section ratio in overlapping bins: PDF's cancel in the ratio
- Ratio directly sensitive to BFKL dynamics.

- R increases with $\Delta\eta$ in contrast to LO QCD

- data behave qualitatively like BFKL (but also like HERWIG)

- given that we can't predict the 630/1800 GeV ratio of inclusive cross sections, how much can we really infer?





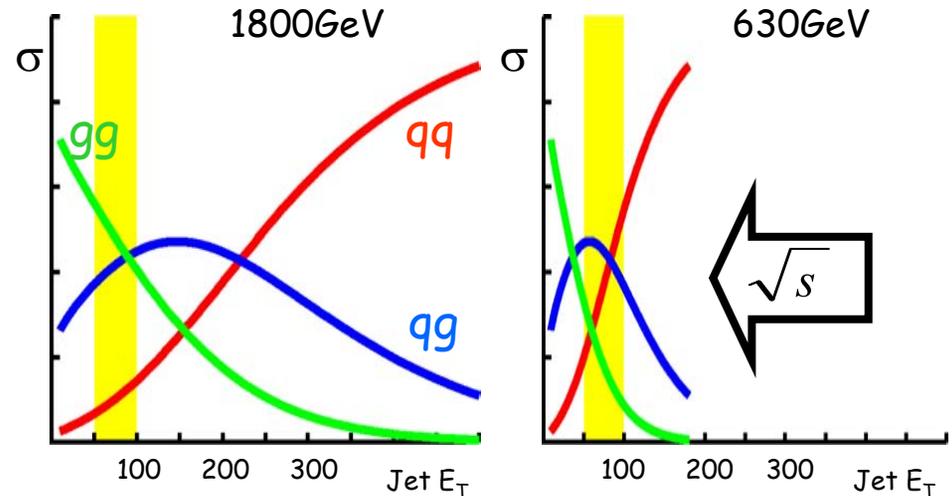
Subjet Multiplicity in Quark & Gluon Jets

Motivation:

- Separate q jets from g jets (top, Higgs, W +Jets events)
- Test $SU(3)$ dynamics (QCD color factors)
- ➔ Measure the subjet multiplicity in quark and gluon jets

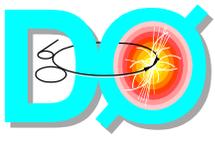
Method:

- Select quark enriched & gluon enriched jet sample and compare jet properties
- ➔ challenge is not to bias the samples.



Contributions of different initial states to the cross section for fixed $\text{Jet } E_T$ vary with \sqrt{s}

➔ compare jets at same (E_T, η) produced at different \sqrt{s} & assume relative q/g content is known.



Subjet Multiplicity in Quark & Gluon Jets

Method:

- Subjet Multiplicity $M = f_g M_g + (1-f_g) M_q$
(g jet fractions f_g obtained from theory)

$$f^{630} = 33\% \quad f^{1800} = 59\%$$

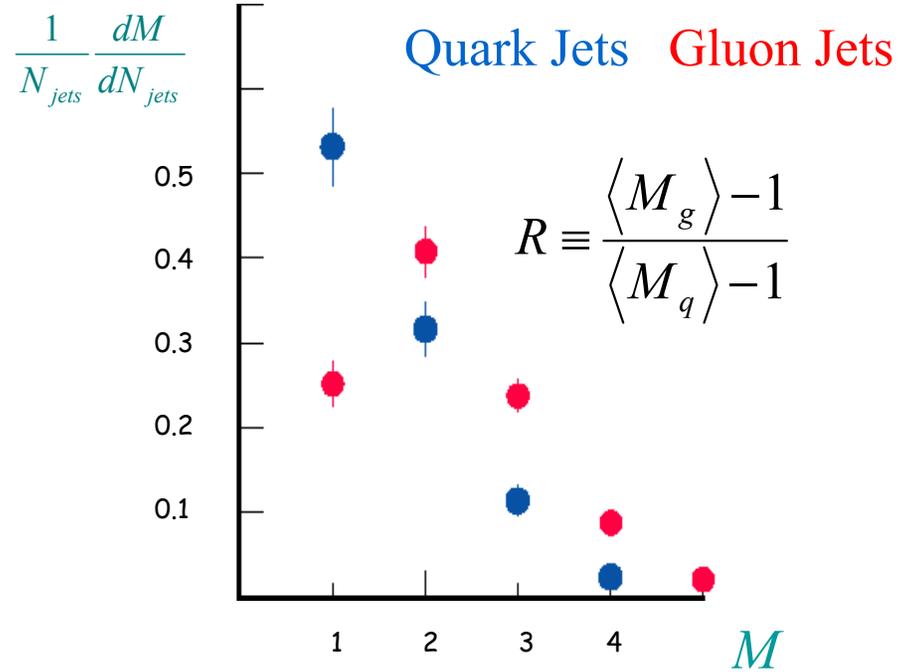
- Assuming that the subjet multiplicity is independent of \sqrt{s} (verified with MC)

$$M_q = \frac{f^{1800} M^{630} - f^{630} M^{1800}}{f^{1800} - f^{630}}$$

$$M_g = \frac{(1-f^{630}) M^{1800} - (1-f^{1800}) M^{630}}{f^{1800} - f^{630}}$$

- Use k_T algorithm; unravel jets until all **subjets** are separated by $y_{\text{cut}} = .001$
- Measure number of subjets for events with jets with $55 < E_T < 100 \text{ GeV}$

$\sqrt{s} = 1800 \text{ GeV}$ Preliminary

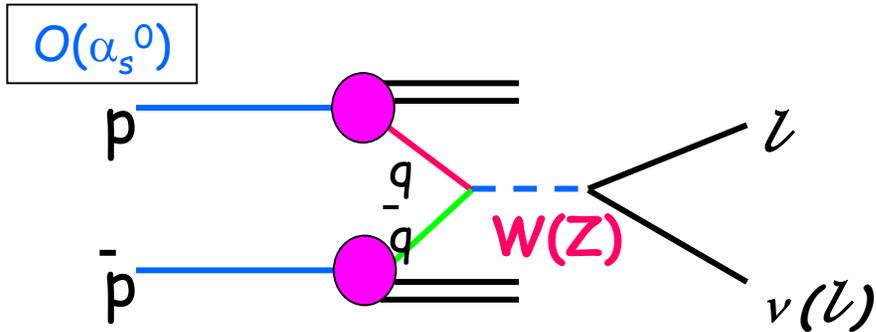


$$R = 1.91 \pm 0.04 \text{ (stat)} \pm \begin{matrix} 0.23 \\ 0.19 \end{matrix} \text{ (sys)}$$

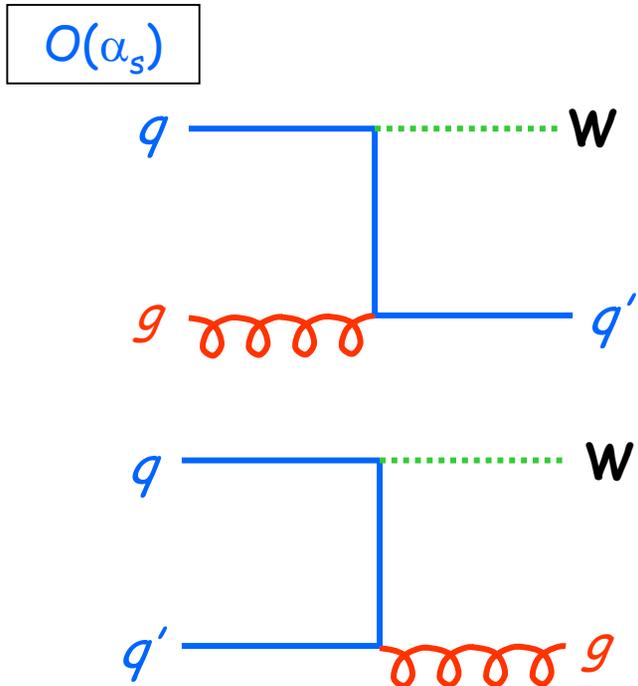
MC Prediction = 1.86 ± 0.08 (stat)

Dominant uncertainties come from g jet fraction and choice of $\text{jet} E_T$

W&Z Production at the Tevatron



- Production dominated by $q\bar{q}$ annihilation (~60% valence-sea, ~20% sea-sea)
- Due to very large $pp \rightarrow jj$ production, need to use leptonic decays (BR ~ 11% (W), ~3% (Z) per mode)



Modifications due to QCD corrections:

- Boson produced with transverse momentum ($\langle P_T \rangle \sim 10 \text{ GeV}$)
- Boson + jet events possible ($W + 1 \text{ jet} \sim 7\%$, $E_T^{\text{jet}} > 25 \text{ GeV}$)
- Inclusive cross sections larger (K factor ~ 18%)
- Boson decay angular distribution modified

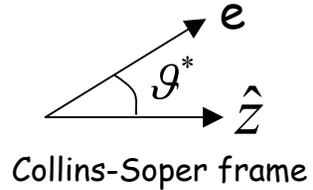
Benefits of studying QCD with W&Z Bosons:

- Distinctive event signatures
- Low backgrounds
- Large Q^2 ($Q^2 \sim \text{Mass}^2 \sim 6500 \text{ GeV}^2$)
- Well understood Electroweak Vertex

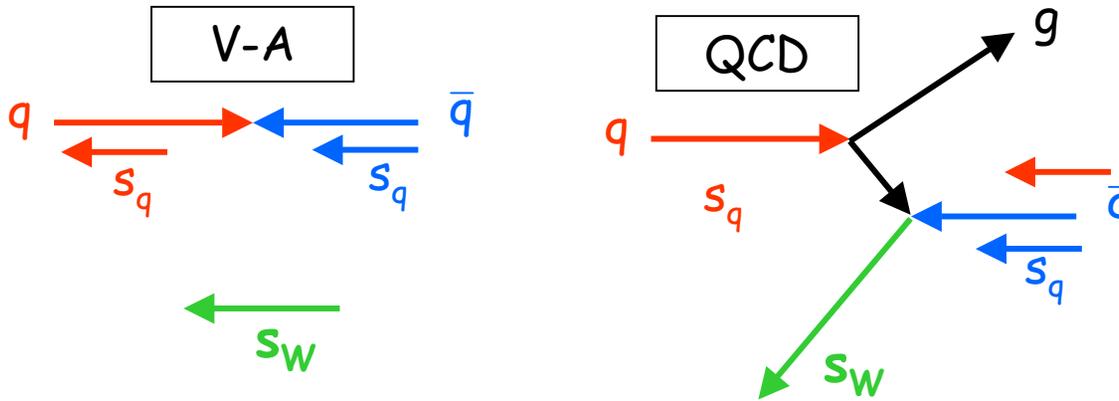
W Decay Distribution

Angular distribution of electron in W rest frame:

$$\text{Pure V-A: } \frac{d\sigma}{d \cos \vartheta^*} \propto (1 + P(W) \cos \vartheta^*)^2$$

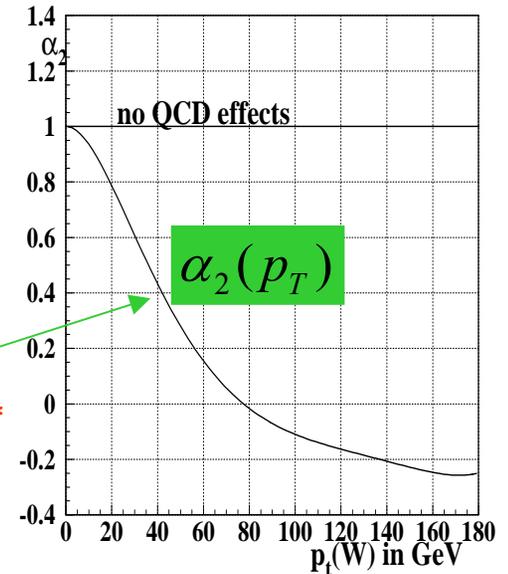


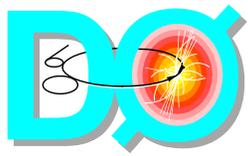
NLO QCD corrections to production modify this distribution:



$$\text{V-A + QCD: } \frac{d\sigma}{d \cos \vartheta^*} \propto 1 + P(W) \alpha_1 \cos \vartheta^* + \alpha_2 \cos^2 \vartheta^*$$

Mirkes, NP B387, 3 (1992) - $O(\alpha_s^2)$.





Method to measure α_2

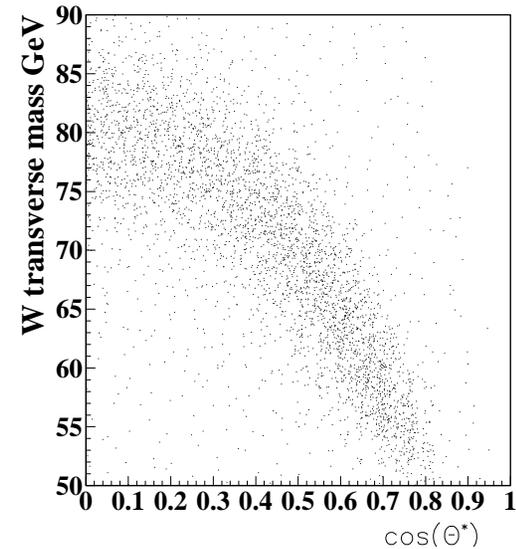
- $P_Z(\nu)$ unknown: W rest frame cannot be reconstructed
- Use correlation between $\cos\theta^*$ and M_T^W to infer $\cos\theta^*$ on a statistical basis
- Define probability function

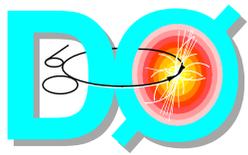
$$f(m_T, \cos\theta^*) = \frac{1}{N} g(m_T / \cos\theta^*) h(\cos\theta^*)$$

- For each $P_T(W)$ bin, plot background subtracted $m_T(W)$ and get

$$n_i = \sum_{m_{Tj}} N_{m_{Tj}} f(m_{Tj}, \cos\theta_i^*)$$

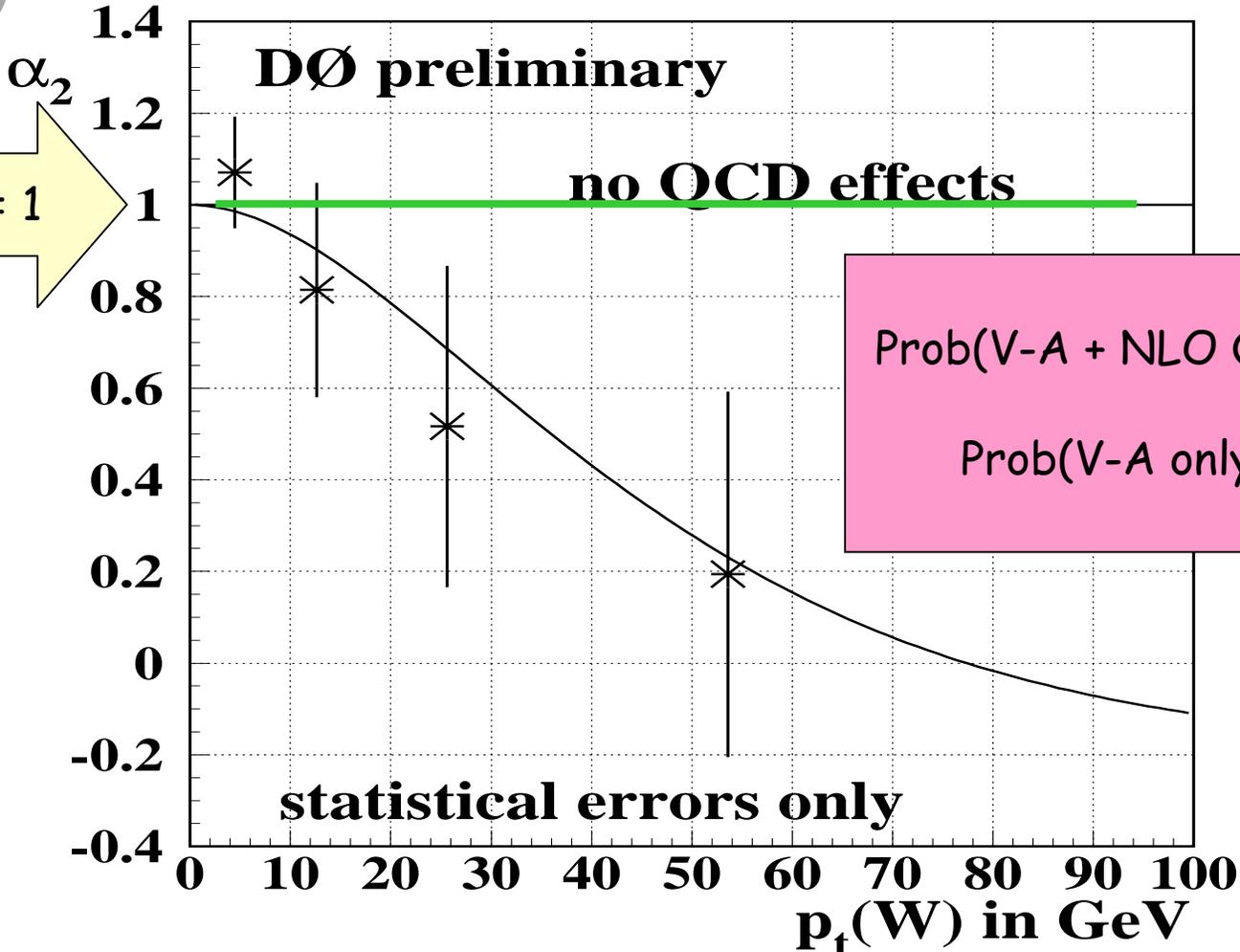
- Compare to n_i templates from MC
- Use log-likelihood to determine best value of $\alpha_2(P_T(W))$





W Decay Distribution - α_2

V-A: $\alpha_2 = 1$



p_T (GeV)	$0 \leq p_T \leq 10$	$10 \leq p_T \leq 20$	$20 \leq p_T \leq 35$	$35 \leq p_T \leq 200$
$\alpha_2(NOL)$	0.99	0.90	0.69	0.23
$\alpha_2(DØ)$	1.07 ± 0.12	0.81 ± 0.23	0.52 ± 0.35	0.19 ± 0.40
systematics	± 0.07	± 0.11	± 0.18	± 0.17

Introduction to $W, Z P_T$ Theory

$$\frac{d\sigma}{dp_T^2} \sim \frac{\alpha_s}{p_T^2} \ln\left(\frac{M_W^2}{p_T^2}\right) \left[v_1 + v_2 \alpha_s \ln^2\left(\frac{M_W^2}{p_T^2}\right) \right]$$

- **Large P_T region** ($P_T \geq 30 \text{ GeV}$): Use pQCD, $O(\alpha_s^2)$ calculations exist

Ellis, Martinelli, Petronzio (83); Arnold & Reno (89);
Arnold, Ellis, Reno (89); Gonsalves, Pawlowski, Wai (89)

- **Small P_T region** ($\Lambda_{\text{QCD}} < P_T < 10 \text{ GeV}$): Resum large logs

Altarelli, Ellis, Greco, Martinelli (84); Collins, Soper, Sterman (85)

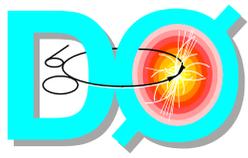
- **Very low P_T region** ($P_T \sim \Lambda_{\text{QCD}}$): Non-perturbative parameters extracted from data

b-space:

Parisi-Petronzio (79); Curci-Greco-Srivastava (79), Davies-Stirling (84); Collins-Soper-Sterman (85); Davies, Webber, Stirling (85); Arnold-Reno-Ellis (89); **AK**: Arnold-Kaufann (91); **LY**: Ladinsky-Yuan (94)

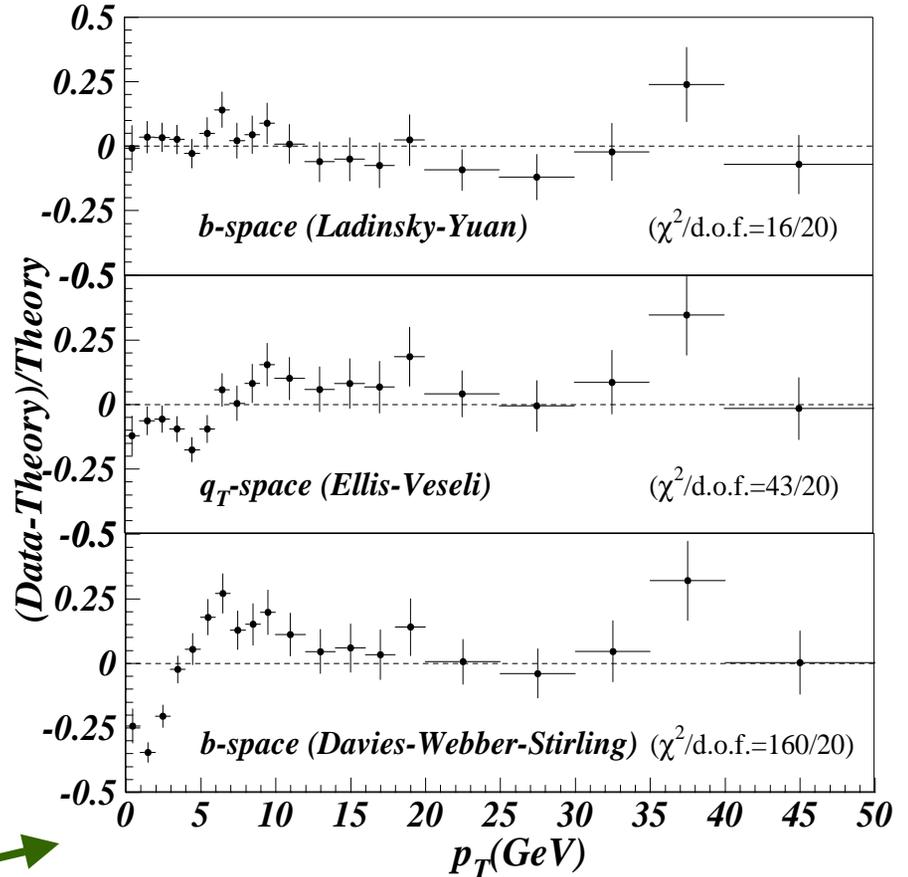
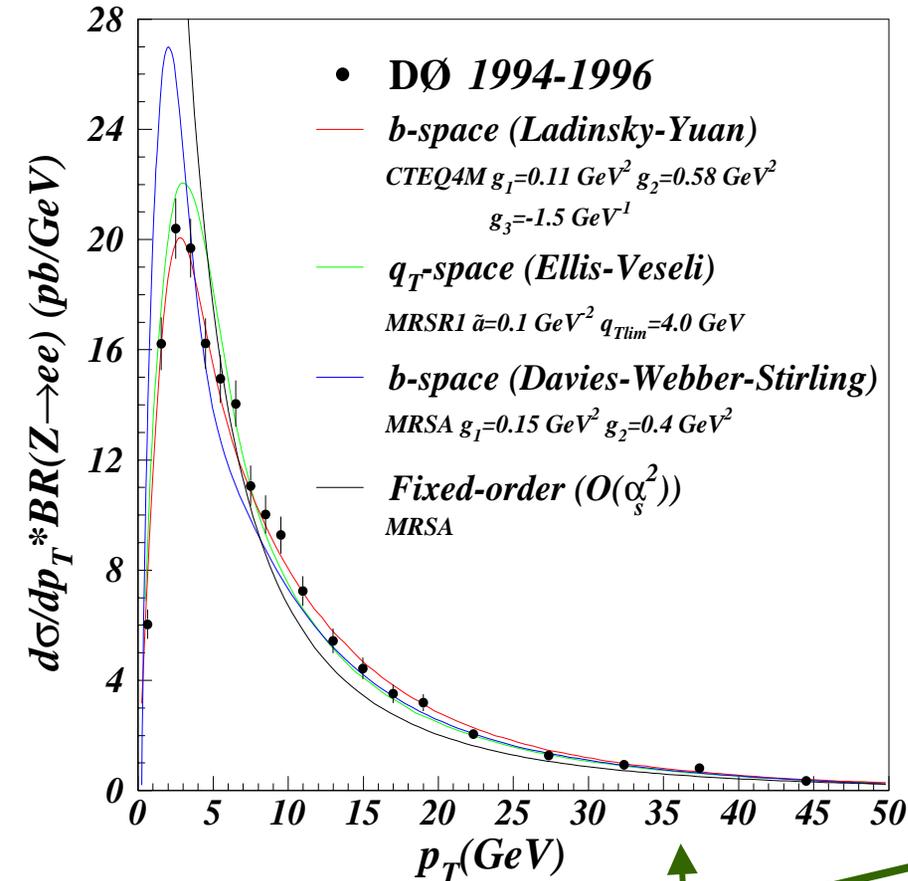
qt-space:

Dokshitzer-Diaknov-Troian (80); Ellis-Stirling (81); Altarelli-Ellis-Greco-Martinelli (84); Gonsalves-Pawlowski-Wai (89); **ERV**: Ellis-Ross-Veseli (97); Ellis-Veseli (98)



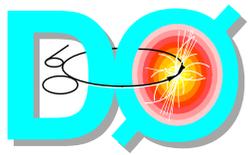
DØ Z P_T measurement

(PRD 61 (2000) & Accepted by PRL)



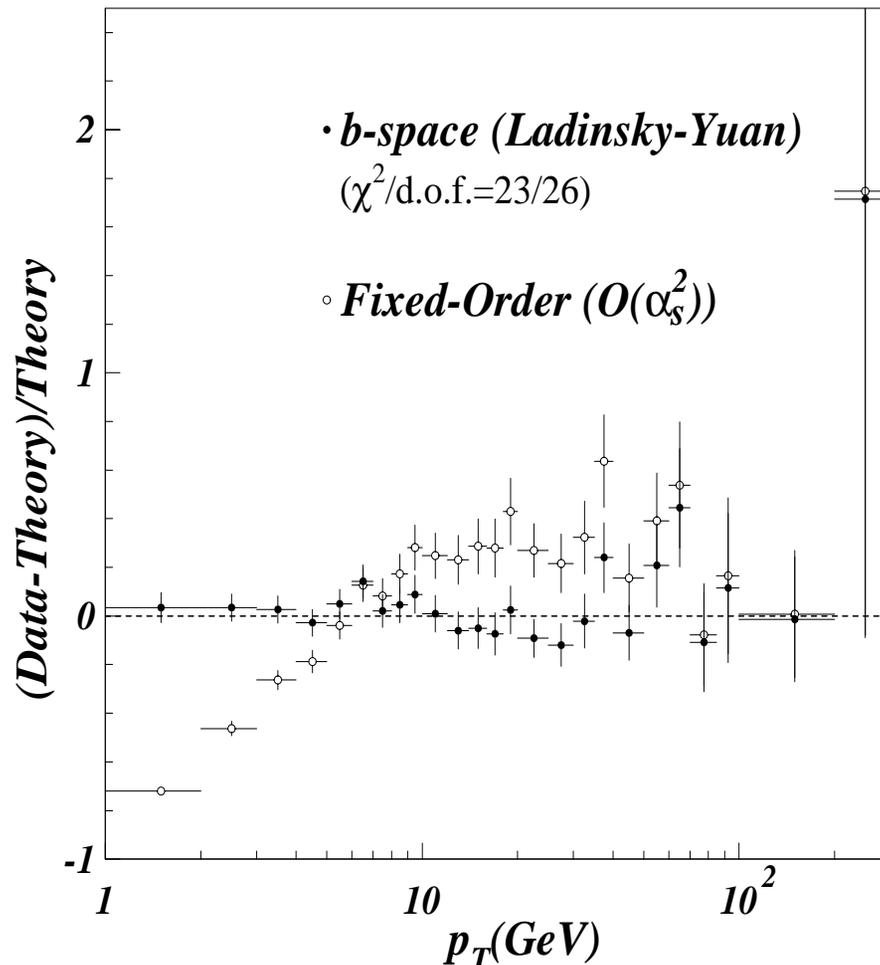
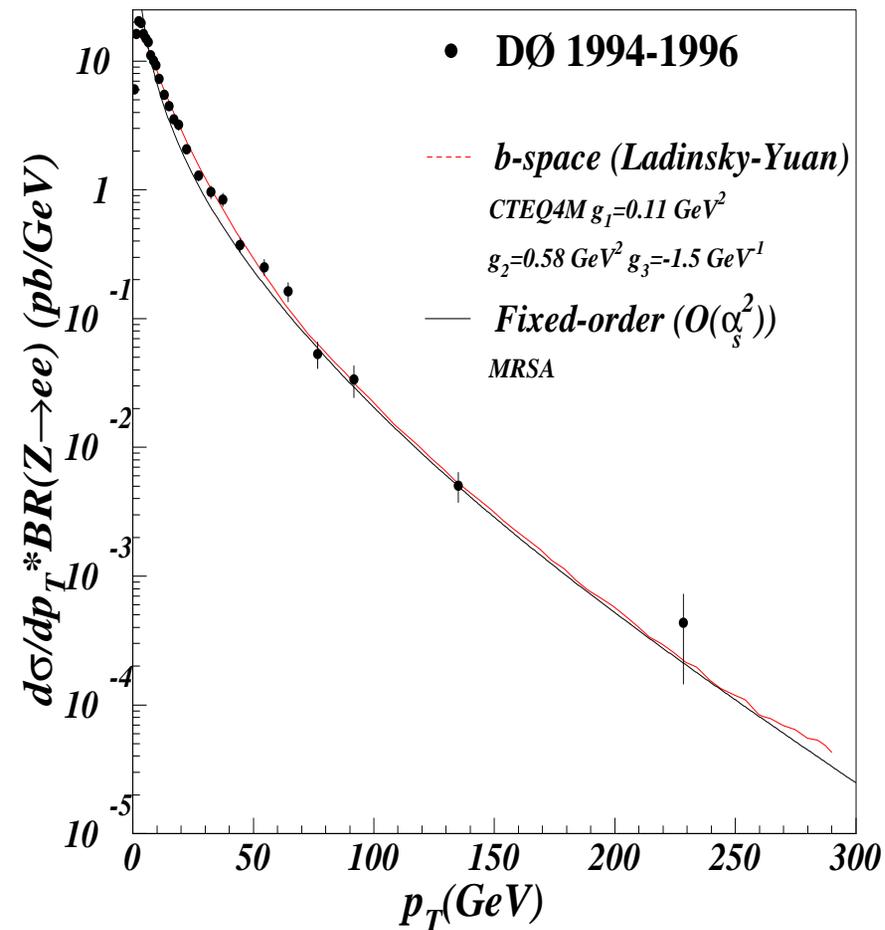
Comparison to **PUBLISHED** parameterizations

Fit to DØ data: $g_2=0.59 \pm 0.06 \text{ GeV}^2$



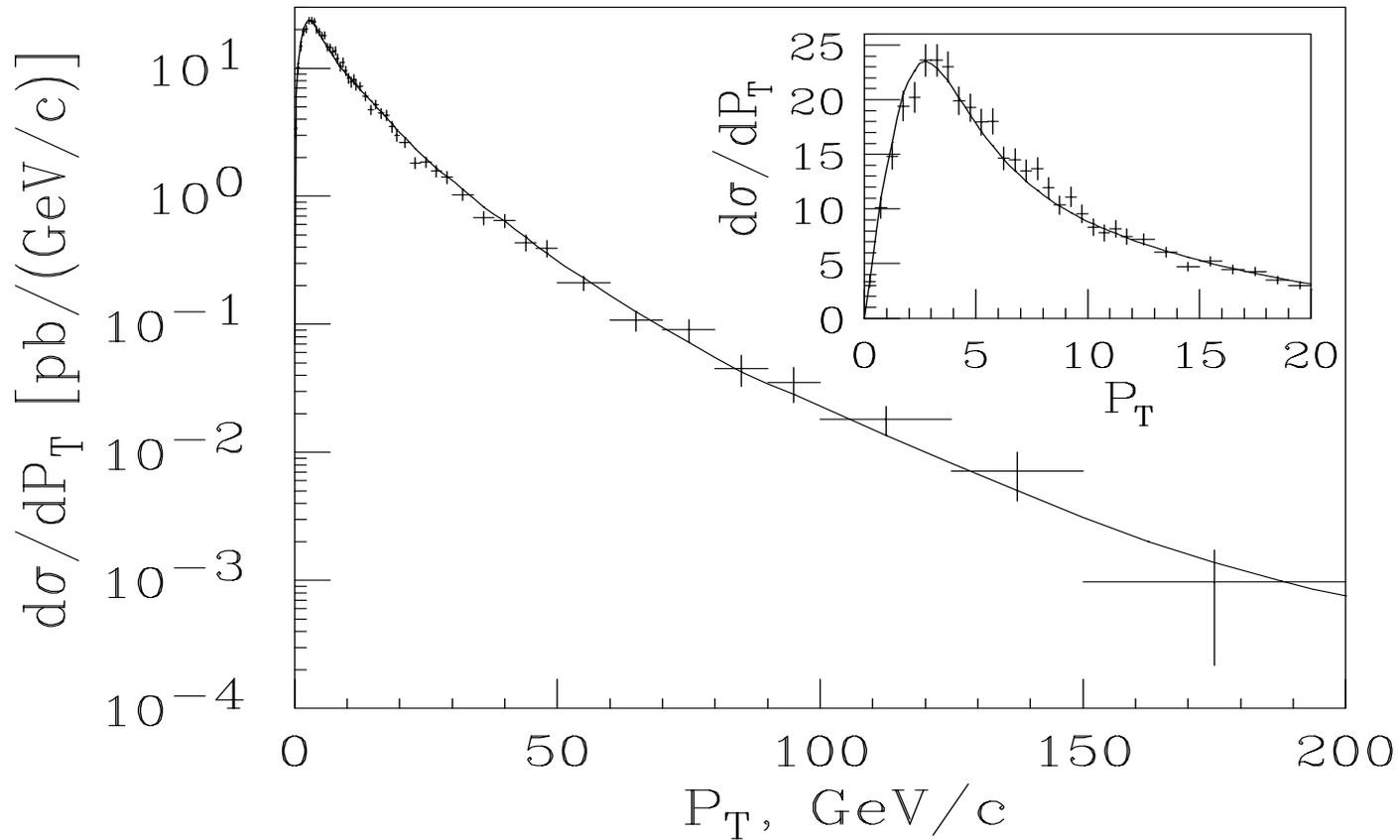
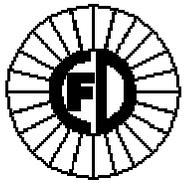
DØ Z P_T measurement

(PRD 61 (2000) & Accepted by PRL)



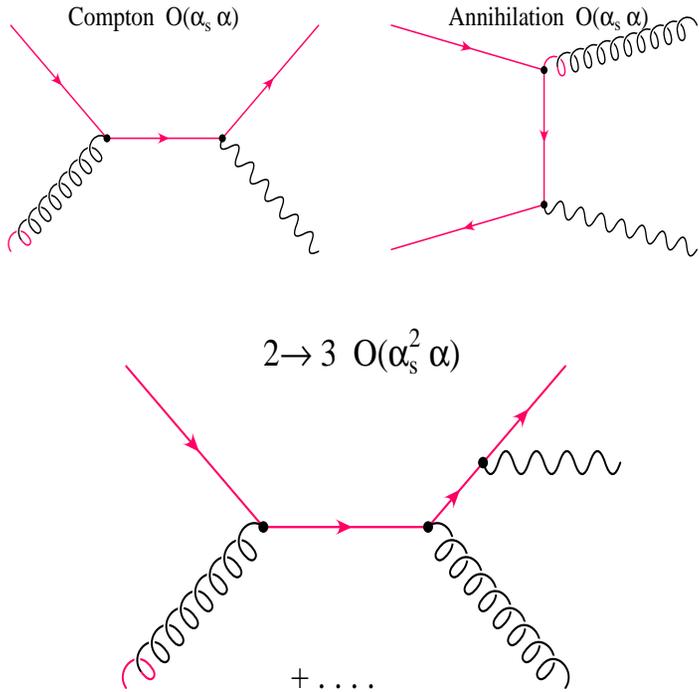
CDF Z P_T measurement

(PRL 84, 845 (2000))



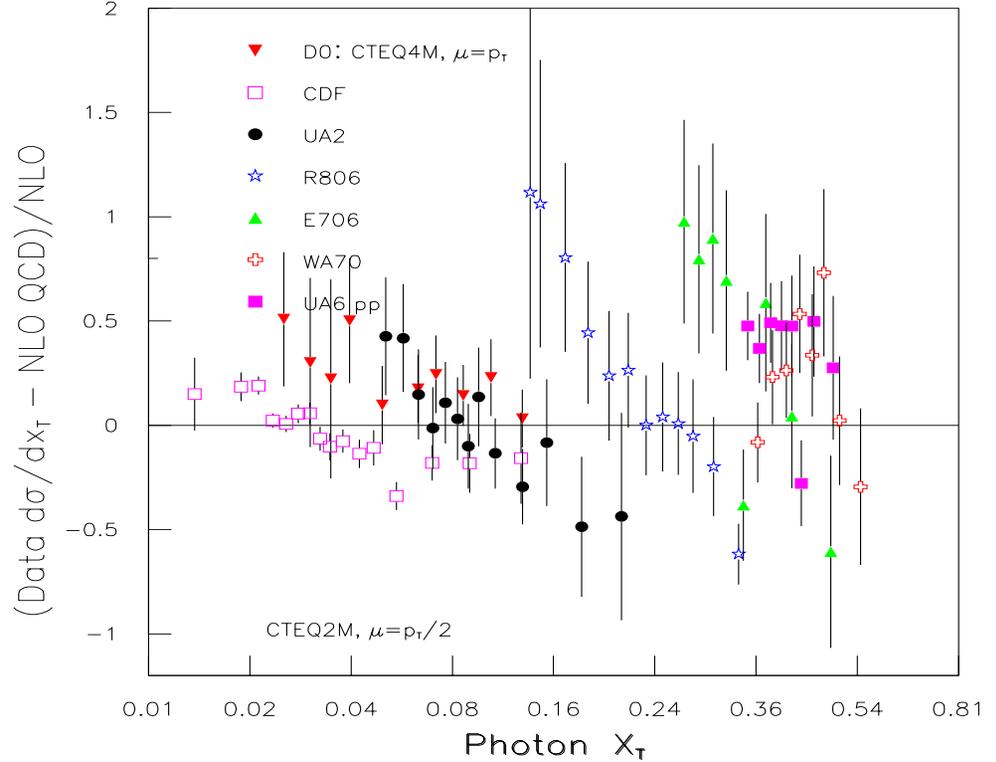
Theory is **RESBOS** Z-only calculation, normalized to the data

Photon production at the Tevatron

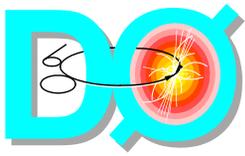


Recent Direct Photon Experiments

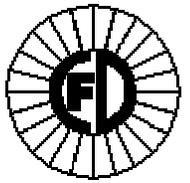
exp	cme	beam	target	Pt	x
CDF	1800	pbar	p	10-130	.01-.14
D0	1800	pbar	p	20-130	.02-.14
E706	~30	p	p, Be,	3-12	.2-.7
	~40	pions	Cu		
UA6	24.3	pbar	p	4-7	.3-.6
WA70	23.0	p pi	p	4-6.5	.35-.55



All the measurements show discrepancies between data and NLO QCD theory.

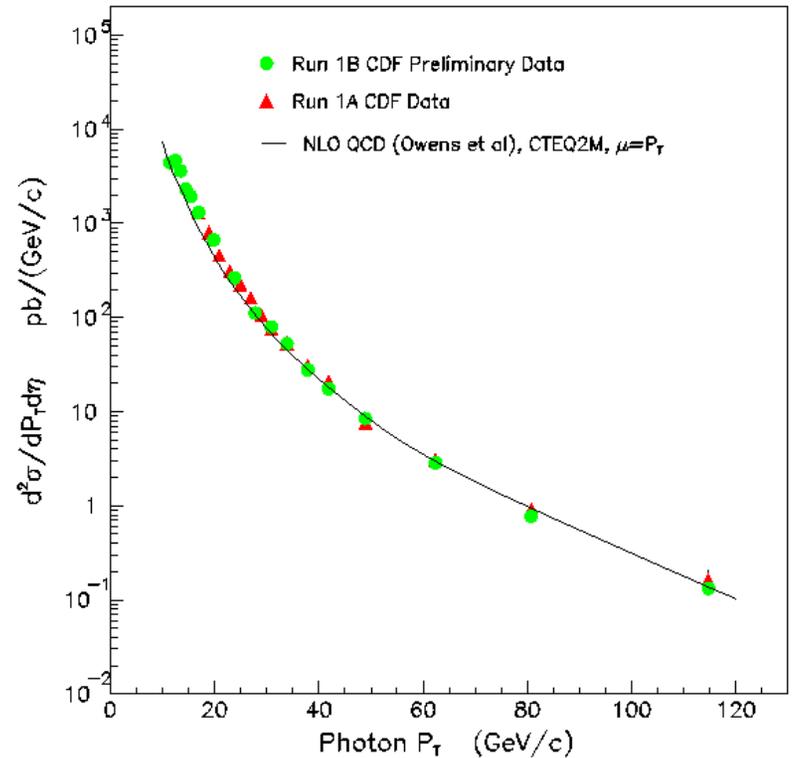
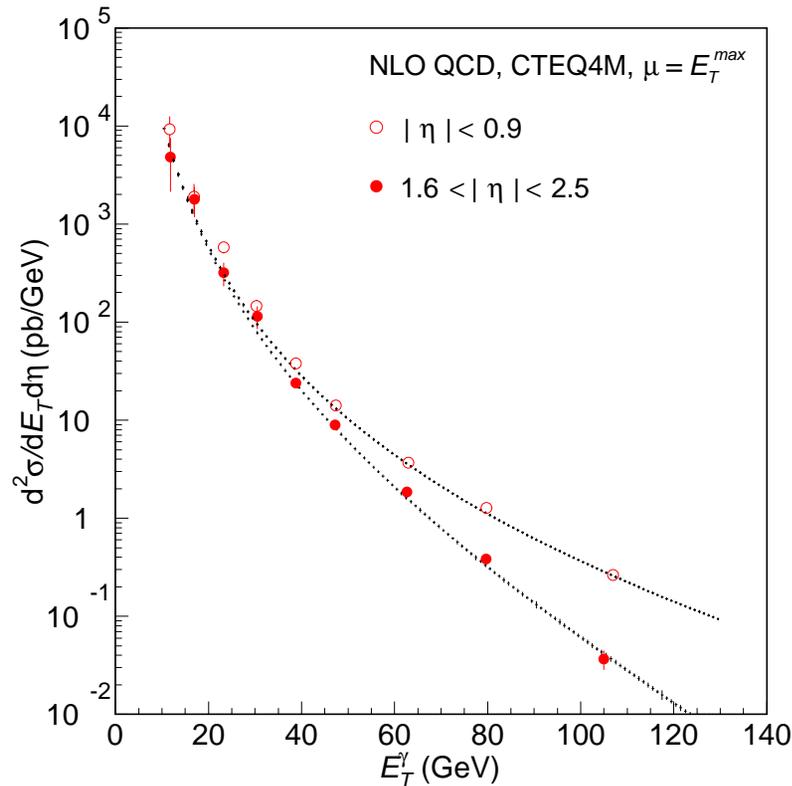


Photon Cross Sections

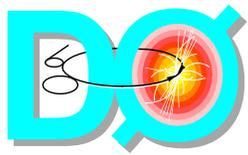


D0, hep-ex/9912017

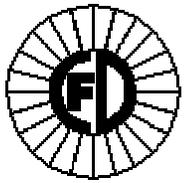
CDF Preliminary



QCD prediction is NLO Owens et al. (PRD 42, 61 (1990))
Note: E_T range probed with photons is lower than with jets



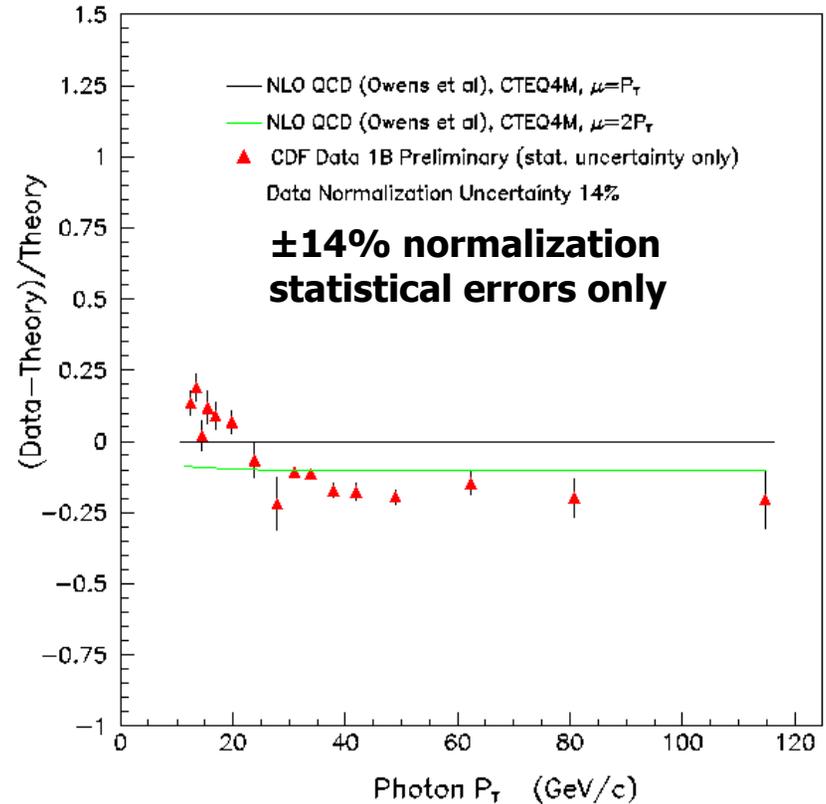
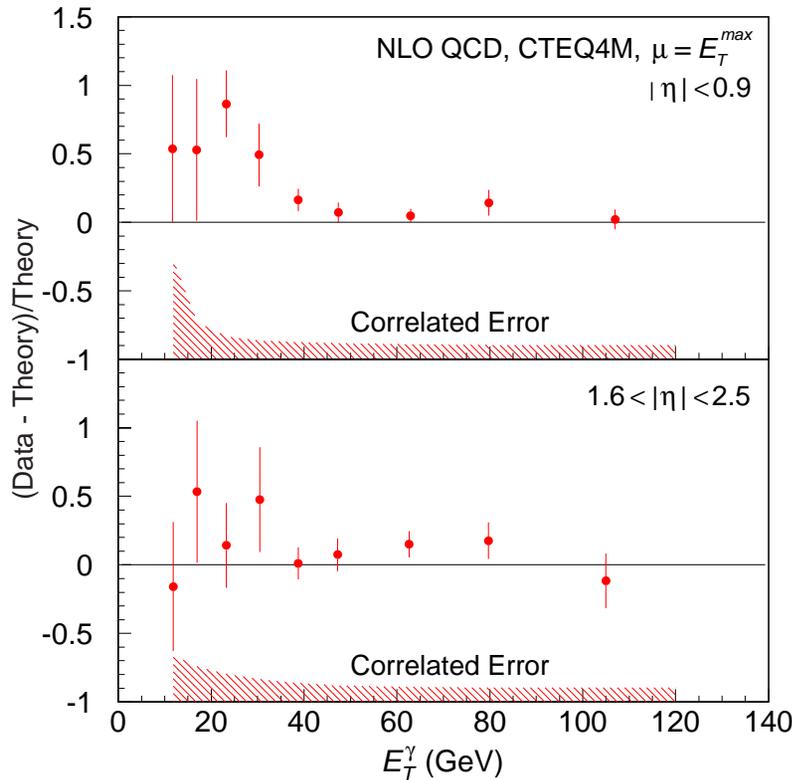
Photon Cross Sections



DO, hep-ex/9912017

CDF Preliminary

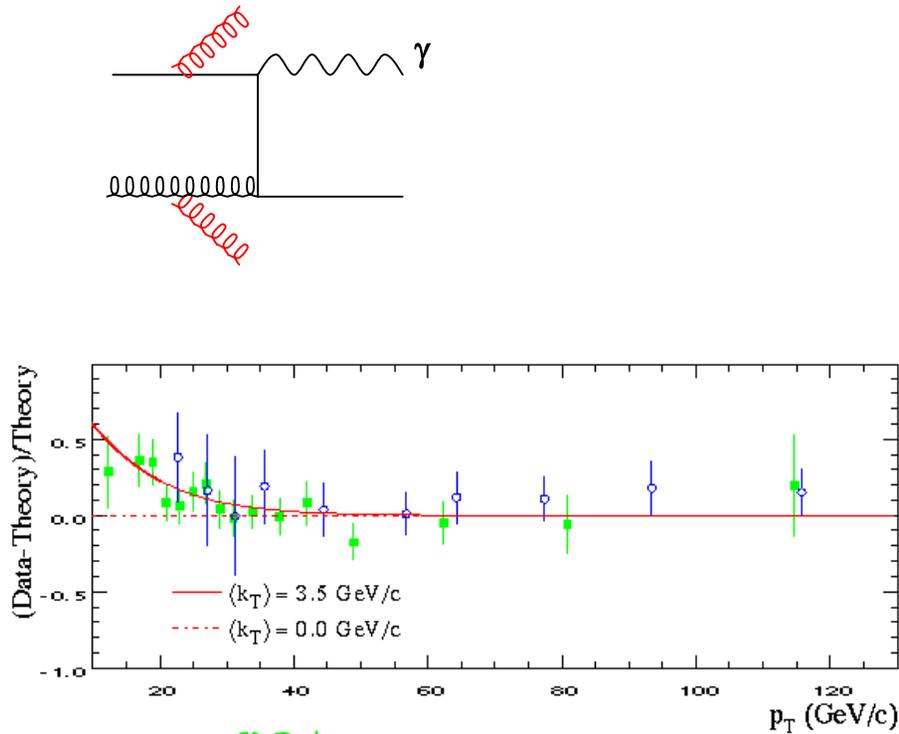
QCD prediction is NLO Owens et al. (PRD 42, 61 (1990))



Good agreement between data and theory for $E_T(\gamma) > 35$ GeV

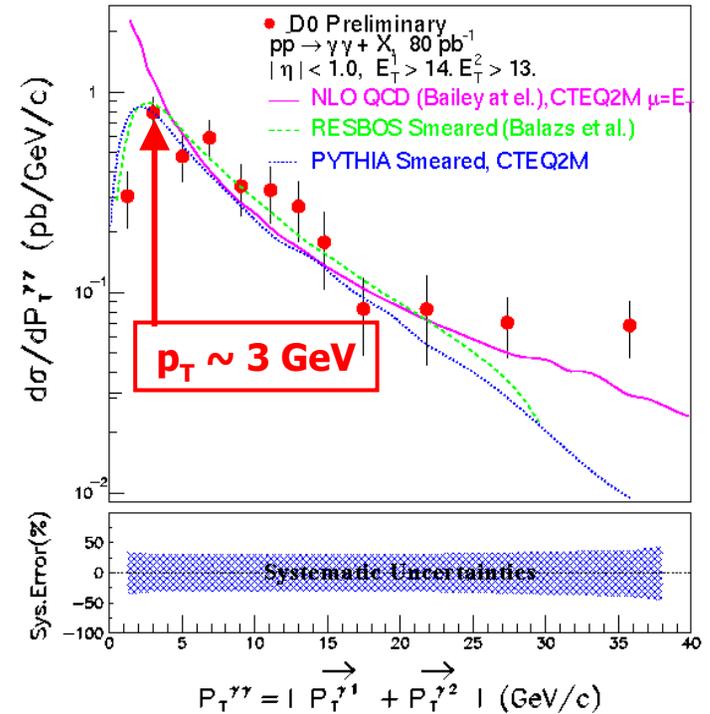
K_T at low E_T

Gaussian smearing of the transverse momenta by a few GeV can model the rise of cross section at low E_T (hep-ph/9808467)

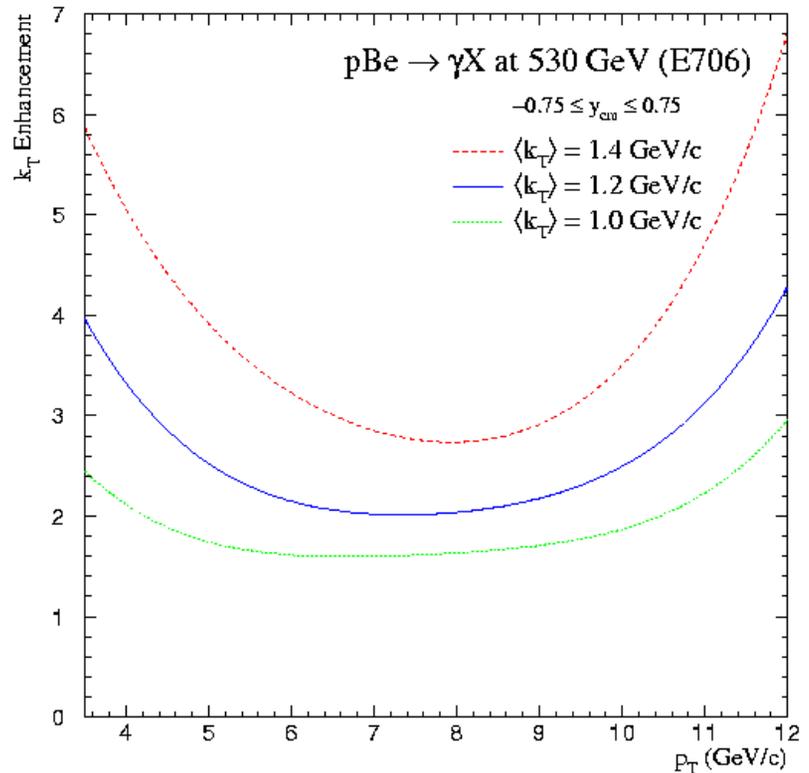
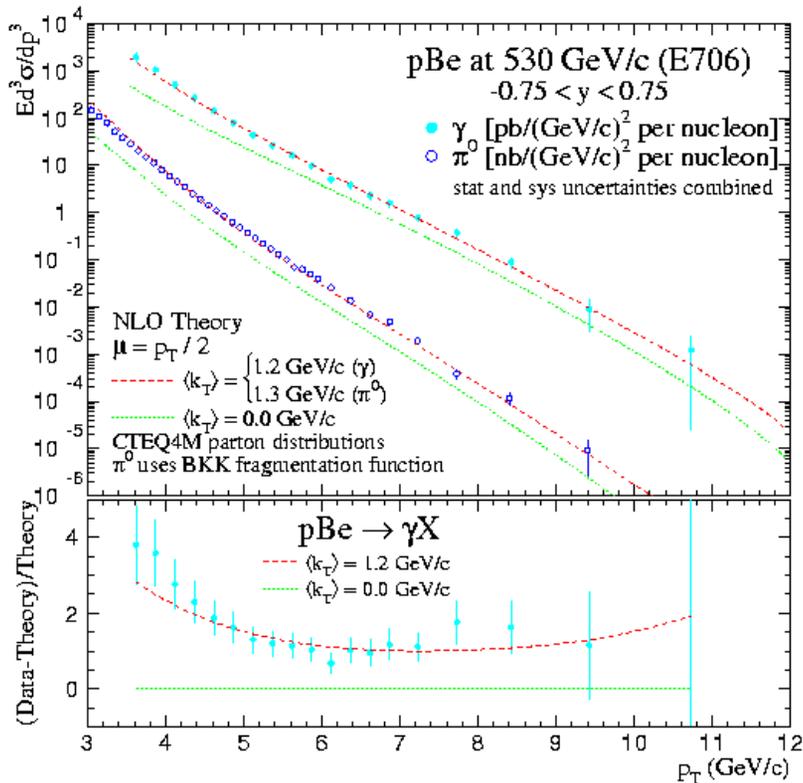


CDF data green
D0 data in blue
NLO QCD in red

Motivated by observed $p_T(\gamma\gamma)$



Fixed Target Photon Production



- Even larger deviations from QCD
- Again, Gaussian smearing ($\sim 1.2 \text{ GeV/c}$)

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Conclusions and Outlook

- New interesting results from the Tevatron on Jet, Photon and W/Z Physics
 - Inclusive Jet Cross sections well described by QCD
 - New results on tests of BFKL dynamics and k_T algorithms
 - New results of Z transverse momentum and W angular distributions
 - Gaussian smearing accounts for measurements of photon production
- ⇒ pbar p collider run to start in March 2001 with $\sqrt{s} = 2.0$ TeV

Many new results still to come

Many thanks to Fermilab Collaborators
from D0, CDF and E706